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THE DESIGN AND THERMAL ANALYSIS OF A HIGH-SPEED TRAIN BRAKE DISC

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Abstract

Brake discs used in high-speed trains are one of the most critical components of these systems. They convert a significant amount of kinetic energy into heat through friction. The high temperatures generated during the process cause thermal stresses, microstructural changes, and surface wear in the disc material, directly affecting its performance and lifespan. Therefore, investigating the tribological and thermomechanical behavior of brake discs is crucial in the optimization of safety, durability, and maintenance costs. In this study, the thermomechanical behavior of brake discs used in high-speed trains will be investigated by use of a computer-aided engineering approach. After modeling the brake disc that satisfies the specific operating conditions, thermal analysis will be performed to obtain values for temperature and heat flux. The variation of these parameters will be presented graphically, and the performance of the brake disc will be analyzed.

Keywords: High-speed train, brake disc, computer-aided design, computer-aided analysis.

INTRODUCTION

The role of high-speed trains in modern transportation systems has increased significantly, and the fundamental elements of safety and performance underlying these operations have become essential. One of the most critical components ensuring the safe operation of trains is the braking system. Brake discs, in particular, play a vital role in stabilizing high kinetic energy during braking and deceleration processes. Fundamental engineering principles such as materials science, thermodynamics, and structural design are important in the design of brake discs developed for high-speed trains. In the literature, many studies have been conducted on the brake discs of high-speed trains. The primary objective of these studies is to enhance braking performance, reliability, and service life to meet increasing speed and safety requirements. While some of these studies focus on the traditional or lighter and more heat-resistant materials such as steel, aluminum or composite materials, others investigate surface coatings and tribological improvements to increase the coefficient of friction, reduce wear rates, and ensure braking stability. Some of the studies also include thermal analysis and design optimization. Ghorbel et al. [1] investigated the fundamental physical mechanisms causing noise and vibration issues commonly encountered in brake systems. The two primary causes of undesired vibrations, coupling mode and gyroscopic effects are determined. Li et al. [2] examined high-speed train brake pads manufactured from different materials. Considering the friction and wear processes during braking, tribological phenomena such as adhesion, abrasion, and thermal and chemical wear were addressed in detail. Mohanty [3] analyzed the performance of aircraft brake systems under different

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climatic conditions. In particular, the responses of carbon-carbon composite brake discs to humidity, temperature, and other environmental factors were analyzed. Ma et al. [4] investigated the wear performance of brake materials during continuous braking, such as long-term and low-intensity braking without emergency braking in high-speed trains, particularly at low temperatures. Li et al. [5] focused on enhancing the steel casting material used in the manufacturing of high-speed train brake discs. It was aimed to overcome the performance limitations of existing brake disc materials, which are typically made from cast iron, and to provide a safer and more durable solution under higher speeds and loads. Mazur et al. [6] conducted a comparative study of the performance of two different types of brake pads used in railway vehicles. By examining cast-iron brake pads and cast-iron composite pads, a scientific basis for railway operators and engineers to select the most suitable type of brake pad under different conditions and requirements was provided. Pachauri et al. [7] performed a finite element analysis (FEA) of the physical phenomena occurring in disc brakes upon deceleration. Thermal and structural effects during braking were analyzed, and by the combination of these analyses, a comprehensive model related to the overall performance and safety of the braking system was presented. Hong et al. [8] investigated the combined thermal and mechanical behavior of high-speed train brake discs. The excessive heat generated during braking and the resulting stresses were analyzed. The data obtained was used in the optimization of material selection, cooling fin design, and braking strategies for brake discs. Choudhary et al. [9] studied the effect of the angle of the ventilation holes in the brake disc on the overall performance of the disc. The primary objective was to find the most suitable ventilation hole angle that could most efficiently dissipate the excessive heat generated while maintaining the structural integrity. Roy and Rao [10] optimized the geometry of ventilated brake discs to enhance the structural integrity of the disc rotor during braking. The number, size, and shape of the ventilation holes were modified to improve critical properties of the rotor, such as thermal stress and mechanical strength. Jiguang and Fei [11] analyzed the performance of high-speed train brake discs, examining the temperature field and thermal stresses on the disc under different brake pad types and sizes. The critical impact of pad design on disc life and safety was investigated. Tsai et al. [12] investigated the dynamics of temperature changes and heat transfer during the braking process. The primary objective was to determine the thermal loads in a disc brake system and the effects of these loads on the material. Xue and Ren [13] provided a comprehensive analysis by combining the complex interactions in the brake discs of high-speed trains across three main physical domains: vibration, thermal and mechanical.

In this study, a computer aided engineering (CAE) approach is performed to a high-speed train brake disc. Initially, a numerical model of the brake disc will be developed to satisfy the prescribed operating conditions. The model will be subjected to thermal analysis to extract critical performance indicators, including, temperature and heat flux, in order to retain its structural reliability and thermal efficiency. In Figure 1, wheel-mounted ventilated brake discs used in a high-speed train is presented.

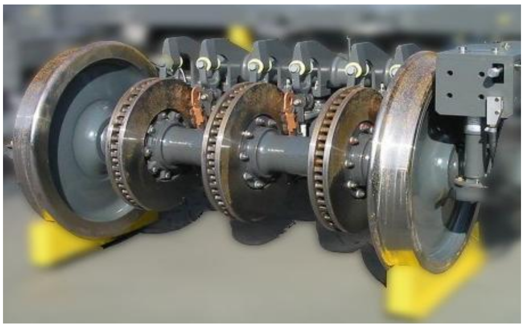

Fig. 1. *Wheel-mounted ventilated brake discs used in high-speed train*

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DESIGN PROCESS

In the study, a computer-aided model of a ventilated brake disc, commonly used in high-speed trains, was developed. During the modeling process, the brake disc used in the study by Sha et al. [14] was taken as a reference. The main geometric parameters of the disc were determined as an outer diameter of 660 mm, an inner diameter of 380 mm, a total thickness of 108 mm, and a 68 mm high ventilation channel. Each friction surface was designed with a thickness of 30 mm, and the contact region between the brake pads and the disc was defined between R195 mm and R325 mm. These dimensions are consistent with the typical proportions reported in the literature for high-speed train brake systems. The isometric view and geometrical dimensions of the brake disc model are presented in Figure 2.

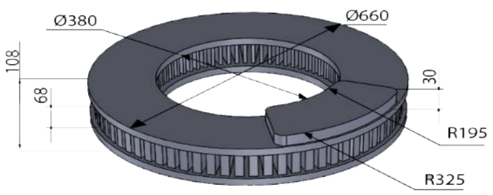

Fig. 2. Isometric view and geometrical dimensions of the brake disc model

The disc geometry was generated in two dimensions by defining the inner and outer diameters, channel gaps, and friction surfaces, and then revolved 360° to obtain the 3-D structure. Subsequently, 72 radial ventilation channels were created to represent the cooling system.

These channels facilitate the removal of heat generated during braking through air convection, allowing a realistic simulation of the transient thermal behavior. In Figure 3, the cross-sectional area and the ventilation channels layout of the brake disc model are presented.

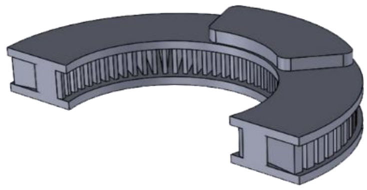

Fig. 3. Cross-sectional area of the brake disc model and the ventilation channels layout

Only the main geometric features influencing the engineering behavior were preserved in the model, while minor details such as bolt holes, flanges, and small structural irregularities were omitted. This simplification was introduced to enhance computational efficiency, improve mesh quality, and ensure numerical stability during the analysis. A similar simplification approach was also adopted in the study of Sha et al. [14]. Consequently, the final three-dimensional model accurately reflects both the geometric characteristics of high-speed train brake discs and a simplified configuration suitable for finite element thermal analysis.

ANALYSIS PROCESS

In the modeling and analysis process, cast steel was used as the material for both the brake disc and the brake pads. The selected material is widely preferred in high-speed train braking systems due to its high mechanical strength, good thermal conductivity, and ability to maintain structural stability at elevated temperatures.

In this study, steady-state thermal and static structural analyses were performed using a finite element analysis (FEA) software. The results obtained from the thermal analysis were sequentially coupled and transferred to the structural model to evaluate the brake disc's overall thermo-mechanical performance. Through this coupled approach, the temperature distribution, thermal stresses, and mechanical deformations of the ventilated brake disc were comprehensively examined under realistic operating conditions.

The rotational speed of the brake disc was defined as 10000 rpm (≈1047 rad/s) to

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represent high-speed operating conditions. To simulate the braking effect, a unilateral heat flux and pressure load were applied on the contact surface, representing the frictional interaction between the pad and the disc. The central hub region of the disc was assigned as a fixed support, restricting translational and rotational motion.

Convective heat transfer was defined on the outer surfaces to simulate air cooling through the ventilation channels, with an ambient temperature of 22 °C and a convection coefficient of 5×10^{-6} W/mm²·°C.

The disc material was modeled as isotropic cast iron, assuming uniform thermal and mechanical properties throughout the geometry. In high-speed train systems, the typical operating speed is around 300 km/h, corresponding to a linear velocity of approximately 83.3 m/s. Considering an average wheel radius of 0.46 m, the angular velocity of the wheel and consequently of the brake disc is calculated to be about 166.67 rev/s.

The mechanical and thermal properties adopted in the analysis are summarized in Table 1. These properties enable the material to exhibit high resistance to sudden temperature variations during braking, maintaining dimensional stability and minimizing the risk of cracking or deformation. Moreover, the high elastic modulus of cast steel helps to limit stress concentrations within the contact region between the disc and the pads, thereby enhancing the mechanical reliability of the braking system.

Table 1 *Mechanical and thermal properties of cast steel*

Property	**Value**	**Unit**
Density	7750	kg/m³
Young's modulus	193	GPa
Poisson's ratio	0.31	-
Bulk modulus	169.3	GPa
Shear modulus	73.66	GPa
Yield strength (tension/compression)	207	MPa
Ultimate tensile strength	586	MPa
Specific heat capacity	480	J/kg·K
Coefficient of thermal expansion	1.7×10^{-5}	1/K

A steady-state thermal analysis was performed to determine the heat distribution on the friction surfaces. The analysis was conducted to examine the general temperature gradients across the disc surface and the heat propagation through the disc volume and the ventilation channels over time. The heat generation due to the applied frictional load on the disc was considered, and the cooling effect of the air channels was incorporated into the model. According to the results, the maximum temperature on the friction surface near the braking region reached approximately 351.91 °C, while the temperature decreased to about 60 °C toward the inner and central regions of the disc. The intense heat generation occurs at the friction contact zone, whereas the radial ventilation channels play an effective role in dissipating the heat through convective transport. The temperature distribution demonstrates that the disc material maintained its thermal stability, confirming that the selected cast steel preserved its structural integrity under high-temperature conditions. Furthermore, the region of maximum temperature coincides with the contact area of the brake pads, showing that the model accurately represents the real operating conditions of the braking system. The temperature distribution of the brake disc is illustrated in Figure 4.

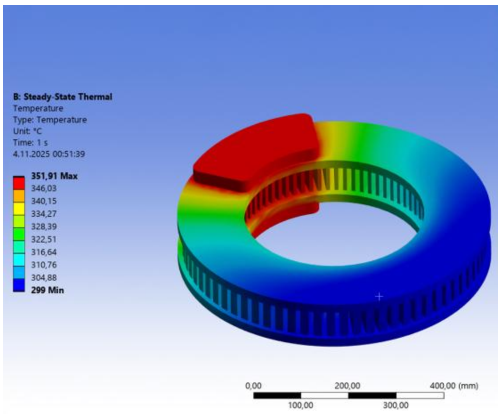

Fig. 4. *The temperature distribution of the brake disc*

In order to investigate the heat distribution on the disc surface during braking, the total

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heat flux analysis was conducted. According to the analysis, the maximum heat flux was found to be 0.0925 W/mm². As expected, the regions with the highest heat flux correspond to the frictional contact areas where the brake pads interact with the disc. The high temperature gradient in these regions causes heat to be conducted radially through the material and subsequently removed by convective cooling through the ventilation channels. The results demonstrate that the brake disc can dissipate heat effectively and that the channel geometry used in the design functions efficiently in terms of heat transfer. The total heat flux distribution of the brake disc is illustrated in Figure 5.

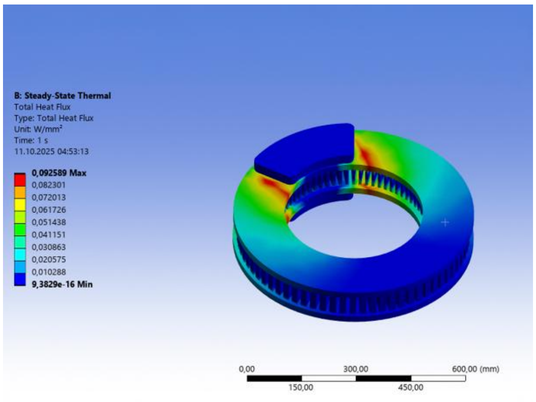

Fig. 5. *The total heat flux distribution of the brake disc*

A directional heat flux analysis was performed to examine the distribution of heat flow components on the surface of the brake disc. The heat propagation along specific axes within the material is evaluated. According to the results, the maximum directional heat flux was found to be 0.0150 W/mm², while the minimum value was -0.0235 W/mm². The presence of both positive and negative heat flux values across different regions indicates that heat transfer occurs in two directions, from the center outward and from the outer surface toward the center. The bidirectional flow results from the asymmetric boundary conditions applied in the model and the unilateral positioning of the frictional contact zone. Since the braking force was applied only on one side of the disc, higher heat flux values (represented in red) were observed on the contact surface, while lower or oppositely directed flux values (represented in blue) appeared on the opposite surface.

The results reveal that heat transfer occurs not only in the radial direction but also has a significant axial component, with the ventilation channels effectively contributing to this process. Although the disc geometry itself is symmetric, the observed asymmetry in heat flux distribution is attributed to the one-sided application of the braking load and the localized heating within the frictional contact area. In Figure 6, the directional heat flux distribution on the brake disc surface is presented.

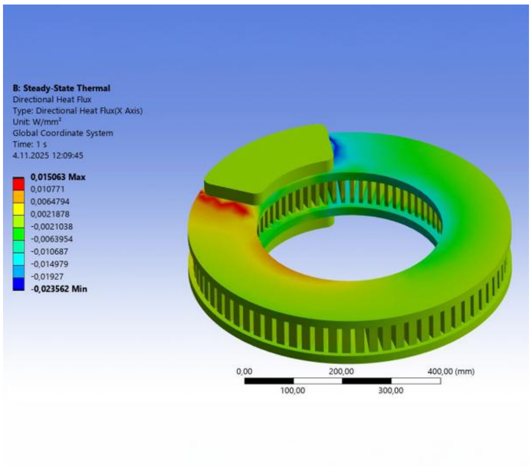

Fig. 6. *The directional heat flux distribution of the brake disc*

In the study, a steady-state CFD simulation was also conducted to analyze the pressure field around the ventilated brake disc at a rotational speed of 10000 rpm.

The velocity and streamline analysis were performed to examine the airflow pattern around the ventilated brake disc. The contour and streamlines illustrated in Figure 8 show the interaction between the external flow and the rotating geometry, revealing both the acceleration regions and the formation of recirculation zones behind the disc. According to the simulation results, the maximum airflow velocity reached approximately 31.1 m/s, occurring near the

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leading edges of the ventilation channels where the air impinges directly on the surface. Behind the disc, two distinct recirculation regions can be observed, where the flow separates from the surface and forms vortex structures (shown in blue zones). In contrast, the high-velocity flow on the front face enhances convective heat transfer, supporting effective thermal dissipation from the frictional surfaces.

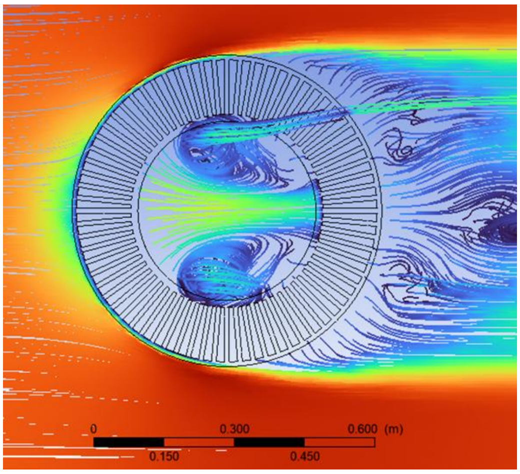

Fig. 8. *Velocity and streamline distribution around the ventilated brake disc*

As shown in Figure 9, the turbulence kinetic energy (TKE) varies notably across the flow domain, revealing regions of strong shear and mixing caused by the rotating geometry and the presence of ventilation channels. The areas near the leading edges and outlet sections of the channels display higher turbulence energy, corresponding to zones of strong vortex formation and shear interaction with the surrounding flow. These regions promote more effective heat transfer by enhancing local convection and increasing air movement along the disc surfaces. In contrast, lower turbulence levels are observed behind the disc and within recirculation regions, where the flow velocity decreases and air mixing becomes weaker. Such areas are prone to localized heat accumulation and reduced cooling performance during continuous braking. Overall, the TKE distribution confirms that the ventilation design efficiently induces airflow disturbance, supporting the cooling process by improving convective heat exchange.

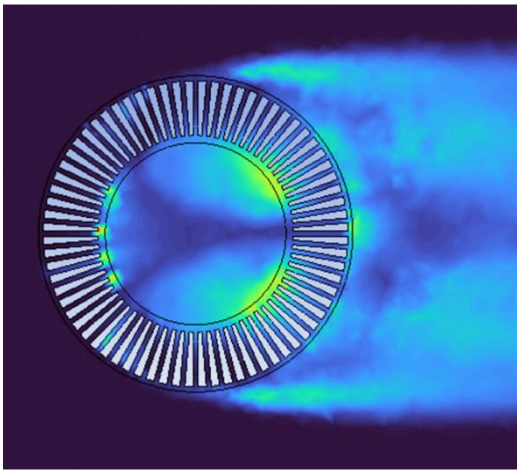

Fig. 9. *Turbulence kinetic energy distribution around the ventilated brake disc*

CONCLUSIONS

To examine the thermal behavior of the brake disc in greater detail, both the total heat flux and directional heat flux parameters were evaluated separately in the analyses. These two parameters describe the magnitude and direction of the heat generated within the disc, enabling a comprehensive assessment of its thermal performance. The total heat flux represents the total amount of energy passing through a unit surface area and includes both the magnitude and all directional components. This parameter was used to determine the overall intensity of heat transfer within the disc. The resulting total heat flux distribution indicated a high rate of energy transfer in the frictional contact regions, with the generated heat being effectively transported along the ventilation channels. Accordingly, the overall thermal efficiency of the disc was assessed based on this distribution. The directional heat flux, on the other hand, represents the component of the total heat flux along a specific axis (e.g., x, y, or $z-$ direction). This analysis was performed to investigate the heat propagation along a given direction (such as radial or axial) and to identify regions where the direction of

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heat transfer changes. This parameter is particularly important for evaluating the cooling performance of the ventilation channels. The combined assessment of these two parameters allows for a three-dimensional understanding of the heat transfer mechanisms within the brake disc, confirming the effectiveness of the ventilation channels and identifying localized temperature increases resulting from thermal imbalance.

In this study, the thermal behavior of a high-speed train brake disc was investigated. The thermal analysis revealed that the maximum surface temperature reached 350.2 °C, which is consistent with the typical operating temperature range reported in the literature. The heat distribution indicated that the temperature concentrated in the frictional contact region was effectively dissipated through the radial ventilation channels, maintaining the disc's thermal stability.

The heat flux analyses showed that the energy transfer was most intense on the friction surfaces, while the directional heat flux exhibited an asymmetric distribution due to the one-sided loading condition. These results collectively demonstrate that the current geometry and material selection provide sufficient mechanical strength and thermal performance under high-speed braking conditions.

For the future work, system efficiency can be improved and thermally induced stresses during braking can be reduced by use of optimization. The optimization parameters will include the number and width of ventilation channels, geometry of the pad contact surface, and material composition.

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